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Experimental study on natural convective heat transfer from a vertical plate with discrete heat sources mounted on the back

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Abstract

An experiment has been performed to investigate the natural convection heat transfer coupled with the effect of thermal conduction from a steel plate with discrete heat sources. Two boundary conditions, with constant heating flux and constant heating temperature, were obtained by controlling the heating flux or temperature of the heat sources mounted on the back of the plate. The heat transfer and temperature distribution of the plate were measured with different heating spaces. By defining the average heating temperature of the plate as the characteristic temperature, simple expressions for the average heat transfer are correlated from the experimental data as a function of the relative heating space and Rayleigh number. The error is ±5% in the Rayleigh number range from 5×10^8 to 5×10^9.

Keywords: Conjugate heat transfer; Natural convection; Discrete heat sources; Experimental investigation

1. Introduction

The heat transfer process with coupled effects of conduction and free or natural convection is common and important because it appears in many practical and industrial devices, such as fin heat transfer, electronic cooling, building insulation, etc. The plate heat transfer of the hot wall heat exchanger used in small refrigerators and solar energy collectors is the typical conjugate problem with discrete heat sources when the heat pipes are treated as the heat sources of the plate. Zinnes [1] investigated numerically and experimentally the coupling of conduction and laminar natural convection from a vertical plate with discrete heat sources mounted on the surface. The results show that the heat transfer calculation according to the isothermal condition is not exact when the thermal conductivity ratio of the plate to the fluid is less than 5000 and the plate temperature variation exceeds 2 °C. The vertical surface temperature distribution and the boundary layer thickness of natural

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convection with multiple isolated heated elements located on an adiabatic surface were analyzed by Jaluria [2,3]. Fins heat transfer coupled with convection, conduction and radiation was investigated numerically and experimentally by Balaji and Venkateshan [4] and Rammohan and Venkateshan [5]. Fujii et al. [6] studied numerically and experimentally natural convection heat transfer to air from an array of vertical parallel plates with protruding and discrete heat sources. The conjugate natural convection with continuous heat source was calculated numerically with the vortex stream method by Vynnycky and Kimvra [7] and Merkin and Pop [8]. Kimura et al. [9] experimented on the conjugate natural convection heat transfer from three vertical plates with different thermal conductivities. A study addressing the electronic cooling problem from the perspective of scaling laws applied to the simple conjugate heat transfer steady shear flow over a heated strip on a flat plate was proposed by Cole [10]. The asymptotic solutions of temperature distribution in a thin vertical embedded strip with non-uniform internal heat generation were obtained by Mendez and Trevino [11]. However, almost all of the above researches were performed with the condition of low Rayleigh number ($<10^8$) and laminar flow. There are few published papers to study natural convection with discrete heat sources for the higher Rayleigh numbers. Because of the absence of heat transfer correlations for conjugate natural convection, the plate of the wrapped type heat exchanger is always considered as the fins of the pipe to compute the heat transfer at present [12,13]. Chen et al. [14] pointed out the limitations of this means.

So, the purpose of the present paper is to study the temperature distribution and natural convection heat transfer of a steel thin plate with discrete heat sources mounted on the back for the interesting case of the wrapped type heat exchanger. Since the numerical model of natural convection in the transition region is fallible, the experiment is performed to investigate the natural convection heat transfer from a vertical plate with discrete strip heaters and to provide the simple *Nu–Ra* correlations about the average heat transfer in the Rayleigh number range from 10^8 to 10^{10}.

2. Experimental apparatus

The experimental setup employed is shown in Fig. 1. The steel plate was 900 mm in height, 500 mm in width and 1 mm thick. The surface was polished in order to reduce the radiation heat transfer. There were nine horizontal strip heaters, named H1–H9, on the back of the vertical plate every 100 mm distance to simulate the discrete heat sources. The strip heaters were made from resistance heating alloys with the diameter 0.12 mm, which were entwined around a micaceous strip with the dimensions of 500 mm (length) × 10 mm (width) × 0.8 mm (thickness). The resistance of every strip heater was $660 \pm 20\ \Omega$. There was a 0.2 mm thick micaceous paper between the plate and the heater for electrical isolation. When the strip heaters were arranged and fixed, instant using foam was used to form a 20 mm thick polyurethane foam layer on the back of the plate, which could make the heaters contact the plate tightly. In order to reduce the heat leak from the back and laterals of the plate, there were 130 mm thick styrofoam ($\lambda = 0.036$ W/(m °C)) between the back of the plate and the support and 50 mm thick styrofoam between the support and the circumjacent edges of the plate. The plate was fixed on the support by four set bolts and the nuts were tightened on the adiabatic rubber mat to minimize the conductive heat through the bolts.

There were 17 thermal couples located on the back of the plate at 50 mm intervals along the central vertical line to measure the temperature distribution. In order to verify the uniformity of the heater temperature in the horizontal direction, another four thermal couples were embedded on the verge of the plate back with 100 mm distance from the left or right edge at different heights. All thermal couples were spot welded on the plate by soldering tin to keep good thermal contact. The wires of the thermal couple were led out along the isotherm on the back of the plate. The temperature at the center of the supporting back was measured by a thermal couple to estimate the leak heat via the adiabatic foam. The ambient temperature was also measured by a thermal couple located at 700 mm distance from the plate surface. All thermal couples were T-type (Cu–constantan). Before the experiment, they were calibrated in a thermostatic bath in the temperature range from 0 °C to 80 °C. A platinum resistance thermometer was laid on the multiplexer to measure the cold junction temperature for compensating the temperature measured by the thermal couples.

The power of the strip heaters was supplied by alternating current. A voltage regulator was used to keep the heating voltage stabilized. The heating power was adjusted by a variable voltage transformer and measured by a power transducer. In addition, the heating power was supervised by a voltmeter and an ammeter. The strip